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Battelle Technical Review

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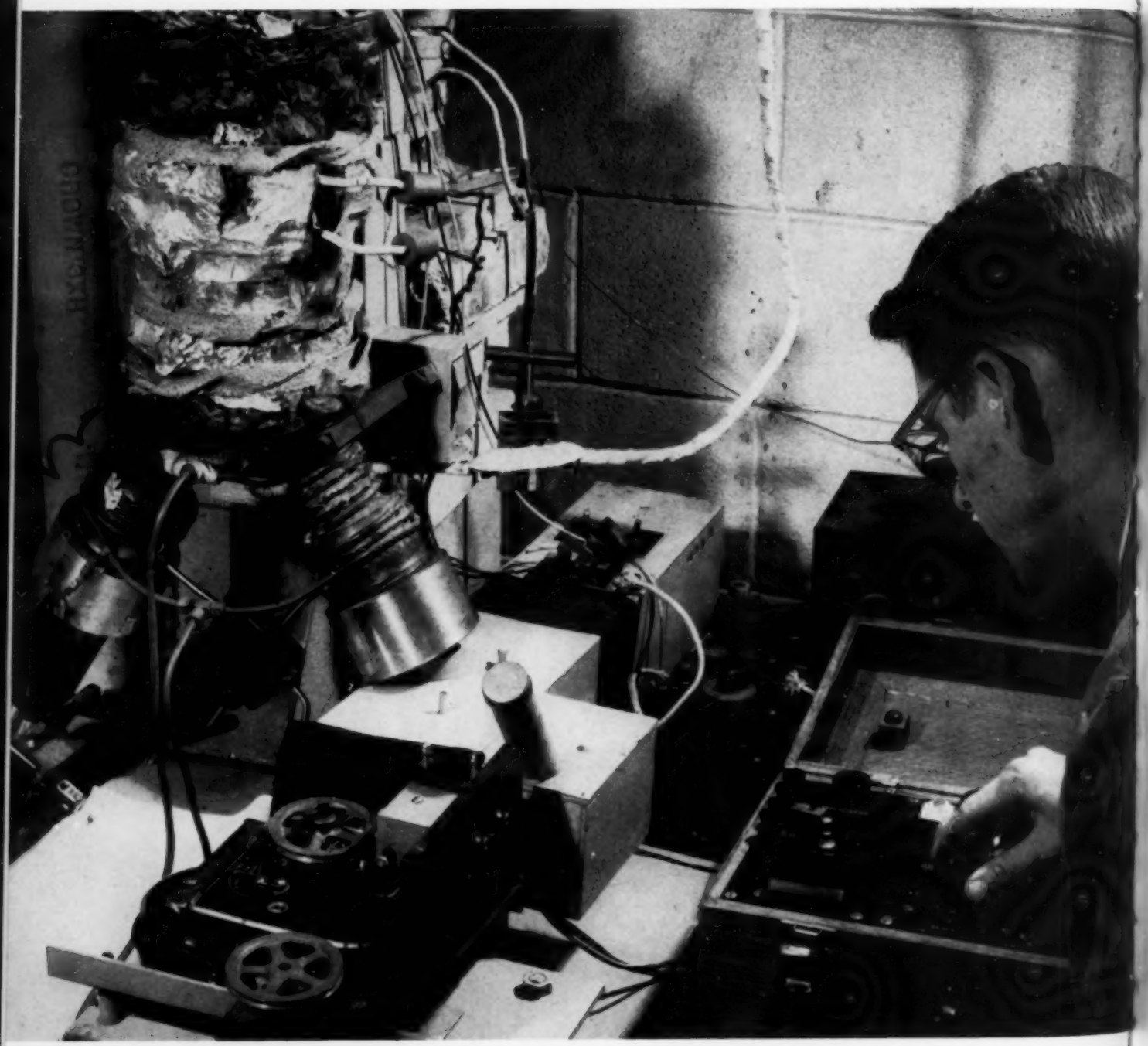
Future Prospects for Nuclear Power

Fine research equipment need not be glamorous. When Battelle technologists needed a means of visually studying corrosion of metals in water at elevated temperatures, they designed and constructed the experimental equipment shown here. They modified an autoclave by fitting it with windows which admit light and permit the taking of photographs and time-lapse motion pictures. It is possible, through the use of a second autoclave for preheating water, to study corrosion of metals from the instant of contact with the water until corrosion is complete, at temperatures to 650 F and pressures to 2000 psi.



VISUAL STUDY OF CORROSION

Volume 5, Number 7
July 1956

BATTELLE TECHNICAL REVIEW

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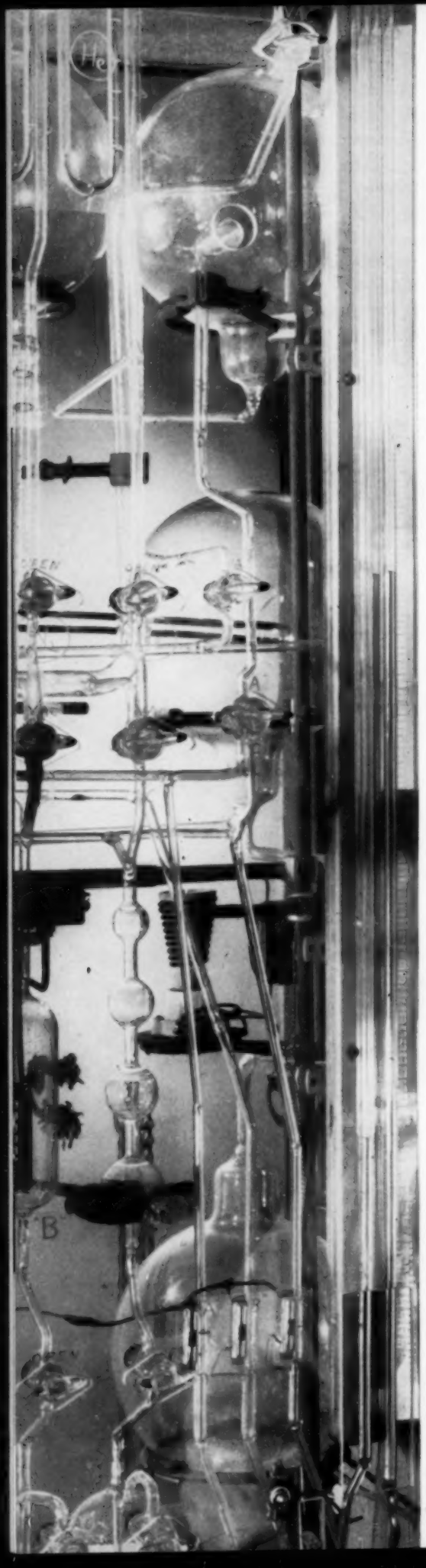

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Abstracts of articles and papers in a wide variety of technological fields from more than 1350 journals published throughout the world. Abstract selection largely reflects the primary areas of Battelle research.

Adsorption apparatus used to determine surface area, porosity, and adsorption characteristics of solids.

World-Wide Challenge to Education

As everyone conversant with current affairs knows, there is a world-wide shortage of technically trained people. Industrial nations prospering through technology are hard-pressed for scientists and engineers to keep their industries functioning. Countries yet to become industrialized need technical people to develop their resources and get workable economies going.

Obviously, if the people of the world are to realize the benefits of industrial science, something must be done to solve this world-wide problem. Educational institutions—the producers of technically trained people—and the political systems responsible for the policies of educational institutions, must rise to the challenge. This, in some cases, may mean the establishment of new concepts regarding the role of education in society and the abandonment of outmoded ideas that still pervade educational philosophy even in highly developed countries.

The technological future, involving as it does atomic energy, fast transport, an industry arising from the research laboratory, and an agriculture based on chemicals and machinery, is an abrupt step from the past. Education must make this step along with other facets of society, and, like these other facets, must take on a technical cast. Above all else, education must look to the future, using the past only for the values it teaches that are applicable to the future. This may mean a de-emphasis of certain traditional studies—particularly those that leave the student unprepared for socially demanded work even though "educated" in the classical sense.

In most countries, the extension of higher education to more people should be a primary objective. This will enable the discovery of more technical talent and will elevate the average educational attainment. The most commonplace tasks in the future will demand educational backgrounds superior to those of the past.

Coupled with the expansion of higher education, there must be an emphasis on science and mathematics courses. Even though the student may not care to be an engineer or a scientist, knowledge of physics, chemistry, mathematics, and biology can better fit him to the modern world. The lawyer, the writer, the salesman, the clerk, the machinist—all will be able to perform their roles more effectively if they understand the basic principles of science.

For the actual training of scientists and engineers, a third requisite is an increase in the numbers and sizes of technical schools. An adequacy of technical schools, either as separate institutions or as divisions of colleges and universities, is required for specialization after the student has obtained his basic education on how to live.

Clyde Williams

President and Director,
Battelle Memorial Institute

VIGNETTE

EXTRACTIVE METALLURGIST

HOWARD C. RENKEN

Extractive metallurgy, still much an art, depends largely upon the experience, skill, and imagination of technologists for many of its successes. There is a continuing effort to transform this field of technology into a science, which only long-range basic research can accomplish, according to Howard C. Renken of Battelle's minerals beneficiation division. In the meantime, the improvement of techniques depends upon patient, persevering work and a willingness to encourage unusual, even revolutionary approaches to problems.

Before joining Battelle in 1943, Howard had built up a broad background of experience which has served him well in his research investigations. After receiving a degree in chemical engineering from the Colorado School of Mines, he was associated with the American Smelting and Refining Company for many years. He started as a nonferrous smelting chemist and was Assistant Superintendent of Operations when he left the firm. During this period he worked on most aspects of the smelting of lead, copper, and zinc. Howard later served as superintendent of the Stauffer Chemical Company's sulfur processing plants in Berkeley and San Francisco, California.

At Battelle, Howard has quietly and competently carried on a series of investigations that have led to solid developments and improvements for various companies. Thus, for a number of years, he played a leading role in the development of a pyrometallurgical process for producing sulfur from pyrite. Now patented, the work began on a bench-scale level and was carried through the pilot-plant stage to commercial production. He has also investigated problems relating to the sintering, nodulizing, briquetting, and pelletizing of ores and other materials.

In another area of activity, Howard's experience and technical knowledge have been valuable assets to Institute teams responsible for evaluations of proposed extractive processes. He frequently participates in such analyses which help to prevent costly errors and aid in determining the economic feasibility of installations.

Howard is an active member of the American Institute of Mining, Metallurgical and Petroleum Engineers, and of the Canadian Institute of Mining and Metallurgy.

Howard's son and daughter are now away at college. At home, his activities are centered primarily in his garden and woodworking shop.

Future Prospects for Nuclear Power

Competitive nuclear power may be 15 years away. In the meantime, military and research requirements for reactors and equipment will support industrial nuclear activity.

by W. Robert Keagy, Jr.

Over the past two years the American public in general and industry in particular have demonstrated sharply increased interest in nuclear energy. As a result of the Atomic Energy Act of 1954, which makes available to private interests much information that was previously classified, industrial participation in the further development of nuclear technology is broadening rapidly, and many companies are now facing the task of identifying the significance of this new technology to their own particular interests. In many cases this can be done only after first establishing, either by analysis, prediction, or guesswork, how nuclear energy might develop in use, along what lines, and how rapidly.

In a field as new and as rapidly changing as that of nuclear energy, no such evaluation can be made with any high degree of confidence. There is a great deal of research and development yet to be accomplished before we can hope for widespread utilization of nuclear energy in our peacetime economy. Industrial experience and facilities must be increased enormously before the costs of nuclear power and other uses of the atom can be expected to become commercially interesting. Finally, the role ultimately to be played by the Government with respect to the further development and over-all control of the field requires considerably further clarification.

Despite these uncertainties and the lack of any past industrial experience from which to extrapolate into the future, a brief review of present activities and programs and a consideration of the current state of development of nuclear technology offer some indications of general patterns of activity that might reasonably be expected over the next 10 to 20 years.

This discussion is principally concerned with nuclear reactors and their various uses. Of the many possible applications of nuclear energy in a number of diverse fields, none has so captured the general imagination or offered promise of such great rewards in terms of industrial activity as the possibility of using nuclear energy to generate electric power at a price competitive with present power costs.

The McKinney Panel Report, published early this year, has presented an analysis of the conditions under which nuclear power might be expected to become competitive. This Panel, charged by the Congressional Joint Committee on Atomic Energy to determine the impact which atomic energy might have on other segments of the economy, found itself obliged to establish first some prediction of the rate at which competitive

nuclear power might be added to the total national generating capacity.

Figure 1 shows the costs of nuclear power that were assumed by the Panel, based upon the testimony of many scientific and industrial authorities. These and other data similarly obtained, concerning the geographic distribution of power costs and power demand, were used to establish a rate of growth of nuclear power capacity based upon competitive economics alone.

Figure 2 shows this prediction. Because there is a wide discrepancy between various estimates of future power requirements, these estimates are used to establish upper and lower limits of the nuclear capacity expected to be installed in the next 25 years.

Figures 3 and 4 show the gross dollar markets represented by these data, obtained by multiplying the expected capacity and output by the capital and operating costs respectively. It is seen that in the years prior to 1970, while costs of nuclear power are expected to decline rapidly and installed capacity to grow only slowly, there is a moderately small and constant market for nuclear power reactors and fuel services. After 1970, a very strong growth in this market is to be expected.

It is concluded, therefore, that only after 1970 will competitive nuclear power demonstrate its full effect upon our industrial life and that in the years leading up to that time, other developments and applications may play a more important role in the development of nuclear technology.

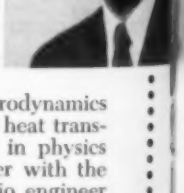
Research and Development

This is certainly true if we regard the research, development, and other programs leading to the eventual achievement of competitive nuclear power as a separate activity. If this is done, it is quite apparent that nuclear power is still very much in the research and development stage and that intense effort and appreciable investments are being made in it. Although these activities are quite broad, three lines of particular importance are identified with the programs of the Federal Government, of the electric-utility industry, and of a group of other companies seeking to establish themselves as suppliers of equipment and services in the nuclear field. A brief discussion of the activities of each of these will illustrate the current interest in reactor development.

AEC Program for Reactor Development

From 1942 until now the Atomic Energy Commission has had a continuing interest in nuclear reactors for many purposes. Among the earliest of these was the demonstration of the principle of the chain reaction and the measurement of certain physical values in the original Fermi pile. Later interest was based upon reactors for use in engineering testing and for scientific research in many fields as well as upon reactors for producing plutonium. Only relatively recently has the Commission's interest been concerned with power reactors, and it was in 1954 that its objectives along this line were clearly set forth as a Five-Year Reactor Development Program. Since then the program has been somewhat expanded and its term extended to indicate that this is an open and continuing effort of the Commission to advance reactor development as rapidly as possible. The present program lists the following projects:

Original Projects	*Responsible Agency*	*Cost (Millions)*
Pressurized Water Reactor (60 MW Elec.)	Westinghouse APD	$85
Experimental Boiling Water Reactor	Argonne	17
Sodium Reactor Experiment	North American Aviation	10
Homogeneous Reactor Experiment	Oak Ridge	47
Experimental Breeder Reactor II	Argonne	40
General Research and Development		42
		$241



Robert Keagy is a member of the staff of Battelle's Office of the Director and is currently working with Battelle's management services department on studies of the economics of nuclear energy. Earlier he helped pioneer Battelle's overseas activities and until 1954 was director of the laboratory at Geneva. When he first joined the Institute in 1946, Keagy participated in investigations in the aerodynamics and thermodynamics of combustion and heat transfer. After receiving his degree of B.S. in physics from Yale, he served as project engineer with the Sperry Gyroscope Company and as radio engineer with the Naval Aeronautical Laboratory at the Naval Air Station, Banana River, Florida.

Activities Incorporated Since 1954	*Responsible Agency*	*Cost (Millions)*
Organic Moderated Reactor Experiment	North American Aviation	$1.8
Liquid Metal Fuel Reactor	Babcock & Wilcox	...
Gas-Cooled Reactor	Unnamed	...

In addition, all of the national laboratories, and in particular Los Alamos, are reportedly at work on various other small reactor experiments.

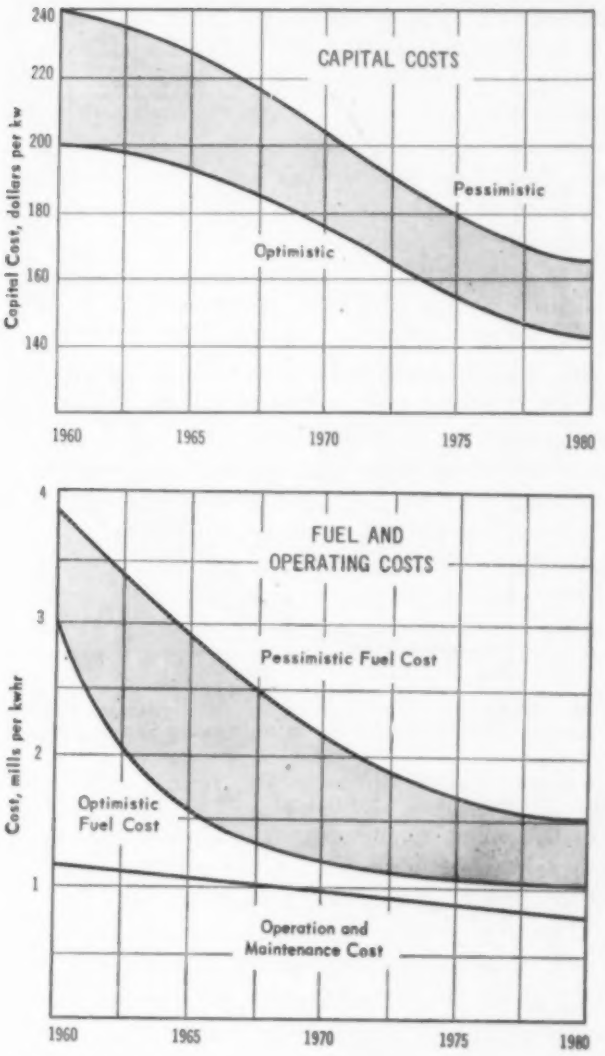
To support these activities the Atomic Energy Commission has spent $18.9 million in 1954 and $25.8 million in 1955. Expenditures for 1956 are estimated at $35.4 million and the 1957 budget requests $38.2 million.

Power Reactor Demonstration Program

Reactor experiments on the scale of those which constitute the greater part of the Reactor Development Program are useful to demonstrate operating principles and permit the study and solution of numerous scientific problems connected with these different principles. These experiments, however, with the exception of the pressurized water reactor, are not of sufficient scale to demonstrate some of the engineering problems that are to be encountered in large power reactors, and they cannot be expected to furnish the all-important economic data required to establish with certainty the costs of nuclear power generated in large central stations.

To supply this information the Atomic Energy Commission, in January, 1955, invited the electric utility industry and others to undertake the construction of a number of large nuclear power stations which, although they could not be expected to deliver power at costs competitive with that from conventional plants, would provide valuable information and demonstrate the engineering problems to be solved. Important forms of Federal assistance were offered including the waiver of fuel charges by the Atomic Energy Commission, the undertaking of some research in federal laboratories, and lump-sum payments for development and operating data obtained from the reactor. In September, a second invitation was issued to the public power companies for the construction of plants on a somewhat smaller scale. This invitation offered the added possibility of the Atomic Energy Commission actually paying the costs of the reactor and retaining title to it.

A number of proposals were received in answer to both invitations. At the same time, a few of the larger



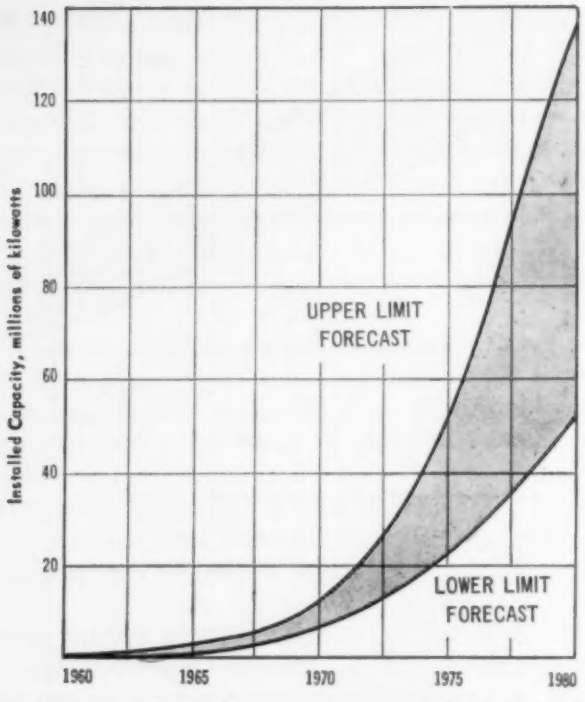
1. *Nuclear power costs assumed by the McKinney Panel.*

utilities, either alone or in groups and sometimes in conjunction with other industrial concerns, applied for licenses to construct power reactor stations to be financed entirely by private means.

Table 1 summarizes the projects proposed to the Commission and indicates that if all are carried out, there should be over one million kilowatts of nuclear capacity installed in the nation by 1963. It should be stressed here that it is not likely that any of these plants will produce power at costs that are competitive with conventional power costs, and these stations, therefore, are not to be included in the predictions of nuclear power capacity growth made by the McKinney Panel.

Other Industrial Activities

In addition to the heavy investments being made by the Government and the electric utility industry, other companies are also investing important amounts in



2. *McKinney Panel forecast of economically competitive nuclear generating capacity in the United States, 1960-1980.*

the development of nuclear power. These are principally boiler manufacturers and manufacturers of other heavy equipment for the utilities plus a few others seeking to establish a position in the field.

The total amount of their investment is quite difficult to estimate. However, Westinghouse is said to have plans for investing over $20 million in atomic development including $6.5 million for a materials testing reactor, and General Electric Co. is reported to be investing on a similar scale. Babcock & Wilcox and Combustion Engineering are both reported to have already spent over $10 million each on studies and facilities for the development of nuclear energy. It is widely believed that many reactor builders now holding contracts to build some of the first demonstration plants have promised to contribute important amounts towards these projects, mostly in the form of research and development done at the manufacturer's expense.

In the field of civilian nuclear power, therefore, a period of intense research and development accompanied by the construction of a number of large demonstration power plants can be foreseen. This work will be aimed at reducing the costs of nuclear power to 7 mills per kilowatt-hour or less. The McKinney Panel estimates that this will require about 15 years and that after 1970 there will be a rapid increase in the growth of nuclear generating capacity on the basis of its economic attraction.

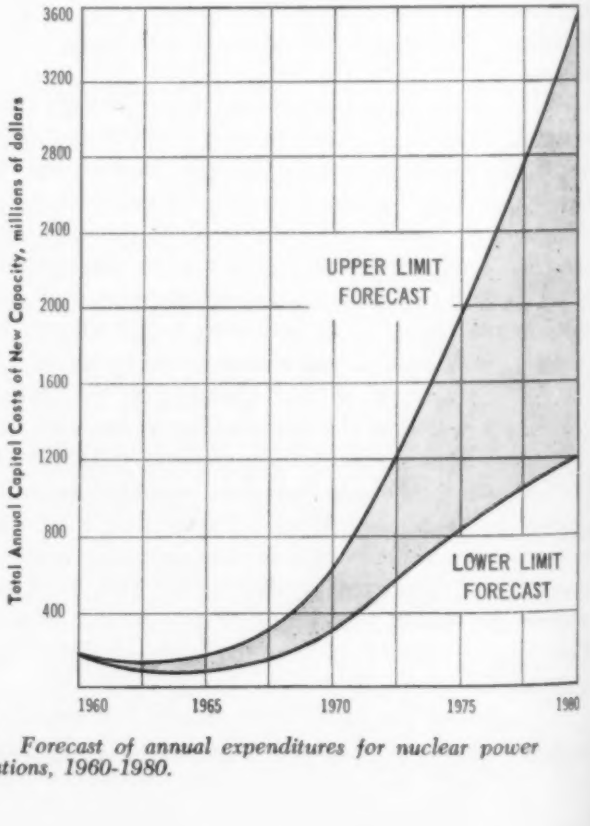
Military Uses of Nuclear Power

The situation with regard to military uses is considerably different. For these, cost considerations are definitely secondary to matters of performance and logistics. A number of areas of military application have been foreseen and discussed. Three programs are sufficiently advanced to be of special interest.

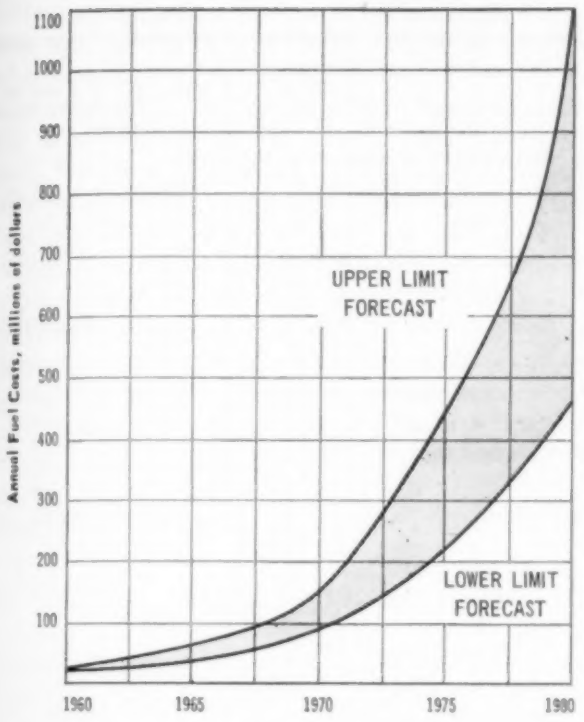
Package-Power Reactors

The Army has particular interest in package-power reactors to provide heat and power at remote and isolated bases, particularly those served by long and vulnerable supply routes. The requirements are much the same as for any small or medium-sized power reactor with added importance given to long fuel cycle, simplicity and reliability of operation, and the transportability of components.

A 2,000 kw prototype reactor is being built at Ft. Belvoir, Virginia, by Alco Products, Inc. under a $2 million lump-sum contract. It is scheduled for completion in July, 1957. Based upon this reactor, the Army intends to install a 1,500 kw plant somewhere in Alaska at an estimated cost of about $4 million. Another development, the Argonne Low-Power Reactor, is under way at the Argonne National Laboratory. Reportedly a boiling water reactor, this plant is to deliver several hundred kilowatts of both electricity and heat.



3. *Forecast of annual expenditures for nuclear power stations, 1960-1980.*



4. *Forecast of annual fuel costs of nuclear power stations operating at 75 per cent capacity. Total costs for United States, 1960-1980.*

To finance these programs, the Atomic Energy Commission spent $600,000 in 1955 and budgeted $1.7 million for 1956 and $3.3 million for 1957.

The construction of some package-power plants at appropriate military sites may reasonably be expected in the years just ahead. However, the uncertainty of future military requirements does not argue strongly for an immediate installation of nuclear power plants at all remote installations. Instead it appears that the Army must be prepared to construct quickly such a plant in any area where supply lines might become threatened. For this reason and in consideration of the low unit cost involved, it appears that package-power reactors for the Army may not represent as large a volume of industrial activity as other uses.

Aircraft Nuclear Power

The use of nuclear energy for the propulsion of aircraft has long been a matter of interest to the Air Force. The problems involved are enormous, but research and development have recently been intensified as the result of what is reported to be a "technological breakthrough". Spending by the Atomic Energy Commission rose from a level of $14.6 million in 1954 to $22.5 million in 1955 and again to an estimated $47.6 million in 1956. The request for 1957 was $74.5 million, marking this as the largest single reactor development program in the Atomic Energy Commission budget.

Despite the heavy expenditures, there is no indication that the difficult problem of accommodating the massive shielding required has yet been solved. Neither has there appeared much comment regarding the performance to be expected from a nuclear powered aircraft apart from the obvious one of unlimited range. It must be noted that present reactor temperatures are far lower than those encountered in today's high-performance jet engines.

The conclusion to be drawn is that the nuclear propulsion of aircraft faces a double hurdle. First, the successful development of nuclear-powered flight must be demonstrated. Second, the resultant aircraft must be judged to be a worthwhile weapon which justifies the tremendous costs of providing special runways, ground-handling facilities, and training programs for both flight personnel and ground crews.

Whether or not the program succeeds in overcoming these obstacles, it appears likely that current efforts will continue to receive top priority for at least another five years by which time the course for the future should be much clarified.

Naval Propulsion Program

While the nuclear propulsion of aircraft is entirely in the research and development stage, such is not the case for naval craft. Nuclear energy is ideally recommended for the propulsion of submarines. The compactness of the fuel can give the submarine essentially unlimited range. Since no oxygen is required and no noxious exhausts produced, this virtue is extended to underwater as well as surface operation. In view of this revolutionary new dimension in performance, the conventionally powered submarine must be regarded as almost obsolete.

Instead, the Navy is pushing ahead aggressively in the development of several reactor prototypes and in the construction of submarines and other craft in which they will be employed.

Reactor development and construction for the Navy is being carried out at three centers. One is the Bettis Field Plant, a development laboratory owned by the Atomic Energy Commission and operated under contract by the Westinghouse Atomic Power Division. This plant has been responsible for the development of the Submarine Thermal Reactor (STR), the Navy's first submarine reactor which, in the Nautilus, has exceeded all expectations of operating performance. The prototype reactor at Arco is being refueled for the first time after 2½ years of operation, and the Nautilus, having travelled 26,000 miles under nuclear power, is expected to go again as far before refueling. The Bettis Plant is also developing a smaller reactor, the Submarine Fleet Reactor (SFR) and a Large Ship Reactor (LSR) for use in surface combat ships. An-

TABLE 1. DEMONSTRATION POWER REACTORS

Company	Reactor Type	Capacity, kw (electrical)	Design Agent	Expected Date of Operation	Cost to Company	Cost to Government
Power Demonstration Reactor Program: First Invitation; Proposed and Accepted						
Power Reactor Development Co. (Detroit Edison Group)	Fast Breeder	100,000	Atomic Power Development Associates	1959	$55,000,000	$ 3,450,000
Yankee Atomic Electric Co.	Pressurized Water	134,000	Westinghouse	1960	33,000,000	7,500,000
Consumers Public Power District of Columbus, Neb.	Sodium-Graphite	75,000	North American Aviation	1959	16,720,000	10,480,000
Power Demonstration Reactor Program: Second Invitation; Proposed						
Chugach Electric Ass'n. and Nuclear Development Corp. of America	Sodium-cooled; D_2O moderator	10,000	Nuclear Development Corp. of America	1961	.....	.....
City of Holyoke, Mass.	Gas cooled—gas turbine	15,000	Ford Instrument Co.	....	($10,000,000)	
City of Orlando, Fla.	Liquid-metal-fuel reactor	25,000 to 40,000	.....	....	.....	.....
City of Piqua, Ohio	Organic moderated	12,500	North American Aviation	1960	.....	.....
Rural Coop. Power Ass'n. Elk River, Minn.	Boiling water	22,000	AMF Atomics, Inc.	1960	($6,000,000)	
University of Florida	Pressurized water	2,000	.....	1959	.....	.....
Wolverine Electric Co. Hersey, Michigan	Aqueous homogeneous	10,000	Foster-Wheeler	....	.....	.....
Privately Financed Reactor Programs: Announced						
Consolidated Edison of New York	Pressurized water; thorium-uranium converter	140,000 plus 96,000 oil-fired superheater	Babcock & Wilcox	1959	55,000,000 (includes superheater)	
Nuclear Power Group (Commonwealth Edison of Chicago	Dual cycle, Boiling water	180,000	General Electric Co.	1960	45,000,000	
Penna. Power & Light Co.	Homogeneous	150,000	Westinghouse Electric	1962	35,000,000	
General Electric Co. & Pacific Gas & Elec. Co.	Boiling water	5,000 to 10,000	General Electric Co.	1957	4,000,000	
Florida Power Corp. Florida Power & Light Co. Tampa Electric Co. Babcock & Wilcox Allis-Chalmers		200,000	Babcock & Wilcox Allis-Chalmers	1962-3	50,000,000	

other center for Navy activity is the Knolls Atomic Power Laboratory, also owned by the Atomic Energy Commission and operated by the General Electric Co. This laboratory has developed the Submarine Intermediate Reactor (SIR), a sodium-cooled reactor operating in the epithermal neutron energy range and now being installed in the Sea Wolf. This second atomic submarine is scheduled for completion this year. The General Electric group is also developing a pressurized water reactor known as the Submarine Advanced Reactor (SAR).

A Third contractor to the Navy is Combustion Engineering, Inc. which early this year received a contract to design, manufacture, assemble and test a small submarine reactor designated the (SRS).

Table 2 lists the various submarine projects planned by the Navy. Nine nuclear submarines are now built or under construction with authorization for six more requested in the 1957 budget. In view of the fact that the submarine fleet now numbers about 200 craft, it is apparent that the present activity represents the beginning of a major program to convert the underwater

fleet to nuclear power. This program promises to constitute the first requirement for reactors, components and services on anything approaching a volume basis.

Plans for the surface combat fleet are only a few years behind the submarine program. Authorization is sought this year to start construction on a nuclear powered 11,000 ton light cruiser to cost an estimated $88 million. Planning for an atomic aircraft carrier is being pushed ahead with authorization for construction expected to be requested in the 1958 budget. At some time between 1960 and 1965 a program for the construction of major elements of the surface combat fleet may be in full operation, and, by this date, nuclear-propelled destroyers may also become practicable. No other program now in progress offers such imminent requirements for a large volume of nuclear reactors and their associated supplies.

Trends in the Use of Nuclear Power

Other requirements for reactors have been postulated. It is generally agreed, for example, that nuclear power may become competitive in foreign power markets before it does in the United States. Sales of American reactors in these markets, however, will meet stiff competition from other countries and will probably be handicapped by Government restrictions on the use of enriched fuel and by payment difficulties.

There is an immediate and growing requirement for research reactors as well as those for training in the fields of nuclear engineering and reactor technology. While the number of such reactors required may be large, the unit cost of each is small in comparison with power or propulsion reactors, and it is difficult to foresee an important volume of reactor business along this line.

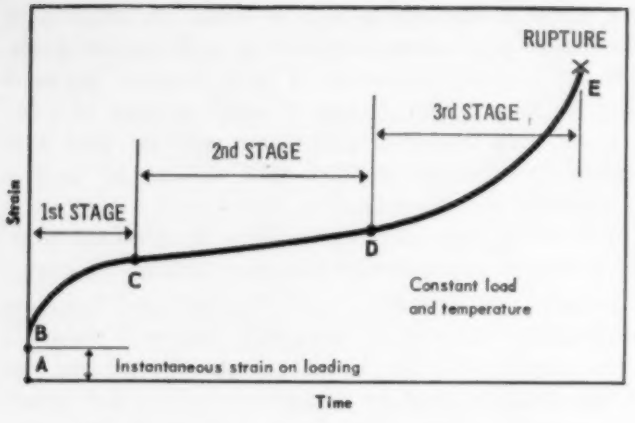
Other uses such as the propulsion of merchant shipping and the generation of process heat have also been discussed, but their development is expected to follow rather than precede the programs discussed above.

In conclusion, the largest single use of nuclear energy that can now be foreseen is for the generation of competitive nuclear power in large central stations. This is expected to become feasible in about 15 years at which time rapidly increasing activity in the construction of nuclear power plants is anticipated. Meanwhile, research, development, and demonstration programs will continue to represent a major part of the activity in the field of nuclear development as will the Navy's programs for reactor development and for construction of units for fleet operation. The aircraft nuclear propulsion program, if successful, will also demand a high level of supporting industrial activity.

It must be remembered that most of the present programs discussed above are only a few years old. Much has been accomplished in those years. Any attempt now to look 15 years into the future may result in as much error as would be found today in a similar attempt made as recently as five years ago.

TABLE 2. U. S. NAVY PROGRAM FOR NUCLEAR PROPELLED SUBMARINES

Number of Units	Designation	Type	Shipbuilder	Reactor	Reactor Cost	Total Cost	Remarks
1	Nautilus		Gen'l. Dynamics	STR	$18,000,000	.....	Operating
1	Seawolf		Gen'l. Dynamics	SIR	....	.....	Launched July 1955—Operation 1956
1	Skate		Gen'l. Dynamics	SFR	....	$ 51,000,000	Authorized 1956
1	Swordfish		Portsmouth, N. H.	SFR	....	51,000,000	Keel laid Jan. 1956—completion 1959
2	.....	Skate—Swordfish	Portsmouth Mare Island	SFR	....	51,000,000 51,000,000	
1	SSN-585	Attack	Gen'l. Dynamics	West PWR	....	.....	Albacore-type hull design
1	.....	Radar Picket	Gen'l. Dynamics	2-reactors	....	103,000,000	
6	.....	3,000 ton	.....	....	....	47,000,000 47,000,000 47,000,000 47,000,000 47,000,000 47,000,000	Requested in budget for fiscal 1957
1	.....	Guided Missile	.....	SFR	....	Authorized 1956. Originally to be conventionally powered. Plans are now to convert to nuclear propulsion.	



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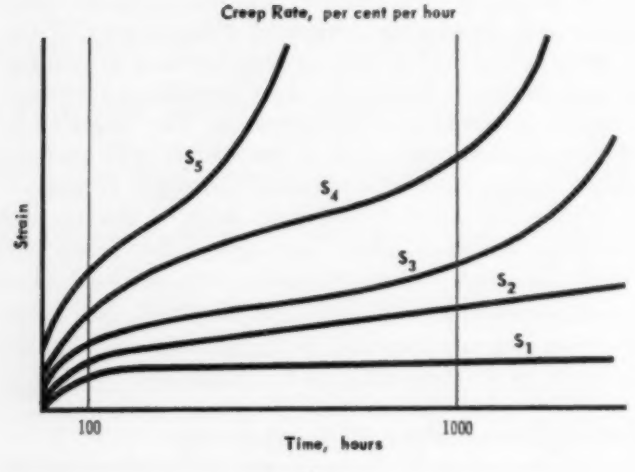

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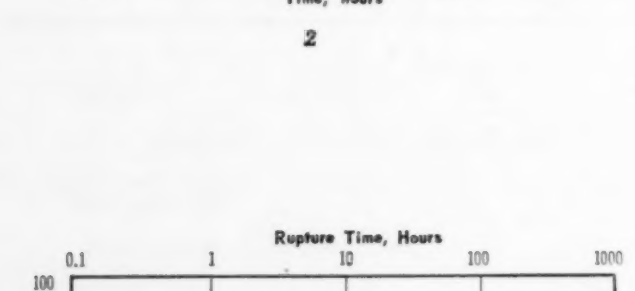

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1. *A typical time-strain curve showing the three stages of creep.*—**2.** *Time-strain curves at constant temperature and increasing load*—**3.** *Log-log plots of stress versus creep rate and rupture time.*

CREEP AND DESIGN

by WARD F. SIMMONS

The need for metals for use at ever-higher temperatures creates design problems which better use of creep and creep-rupture studies can help to solve.

CREEP IS TIME-DEPENDENT flow or plastic deformation of materials under load or stress. It can occur under tension, compression, bending, shear, bearing, or combined stresses. For most engineering structural materials, creep is a design problem only at elevated temperatures. However, in recent years, the use of materials, particularly metals, at elevated temperatures has increased immensely. Also, the maximum temperatures for most applications are increasing, because higher temperatures usually mean improved efficiency of the process, engine, turbine, etc. The trend is always up. For example, in steam power generation the maximum initial steam turbine temperature rose from about 675 F in 1920 to 1050 F in 1950, an increase of approximately 12 F per year.

Although creep in low-melting-point metals had long been known, it was not until J. H. S. Dickenson's paper was published in 1922 that the importance of creep in high-temperature design was generally recognized. The results of his studies showed that metals commonly accepted as suitable for high-temperature service possessed less resistance to failure than had

been deduced from conventional short-time high-temperature tensile tests. Dickenson's work indicated that it was impossible to predict the long-time behavior of metals from tests of short duration; and his publication was followed by intensive study of the creep properties of metals at high temperatures in laboratories all over the world.

Nature of Creep and Rupture Tests

The usual method of carrying out a creep or creep-rupture test is to subject a suitable specimen to a tensile load while it is maintained at a constant temperature. Under these conditions, the elastic or elastic-plus-plastic strain on loading is measured, followed by the measurement of the continuing extension with time. A creep-rupture or rupture test is in essence a creep test at a high load which is continued until the test specimen actually fails. The strain data are usually plotted against time to give the typical time-strain curve shown in Figure 1. Segment AB of this curve is the instantaneous strain on loading, and consists of elastic or elastic-plus-plastic strain. The elastic strain is instantly recoverable when the load is removed. A portion of the inelastic strain is also recoverable over a period of time. The amount of recoverable elastic strain can be computed with some confidence, but the amount of recoverable inelastic strain is governed by laws which are at present quite obscure. Accordingly, when recoverable inelastic strain is important, it must be measured under conditions closely simulating service. The time-dependent portion of the curve begins with segment BC, which is the first stage of creep, characterized by a decreasing creep rate. The second stage of creep CD is represented by a relatively constant creep rate which is also the minimum creep rate measured during the test. The third stage, DE, is characterized by a continually increasing rate of creep until failure occurs at point E.

The plastic strain or creep which occurs in a test specimen, or in a part in service, is largely permanent strain or deformation and, once it has taken place, the life of the specimen or part has been reduced by the amount of the strain. The nature of one type of design problem can be illustrated by the following example. Suppose a turbine blade can deform 1 per cent before it rubs on the casing and that 0.5 per cent of this is elastic strain. This means that when the blade deforms only 2.5 per cent in creep, it has used up three-fourths of its useful life (based on strain, not time). It is obvious then, that when selecting a material for such an application, the amount of creep occurring in the first stage, where the creep rate is quite rapid, is very important. Other things being equal, a material exhibiting a small amount of first-stage creep would be selected.

In high-temperature design, many factors other than strength must be considered. In addition to the strength properties, physical and mechanical properties such as oxidation or corrosion resistance, thermal expansion and conductivity, damping capacity (ability of material to absorb vibrations), mechanical and thermal-shock resistance, notch sensitivity, behavior under cyclic stress and temperature conditions, and other properties must be considered. Also the designer must have a complete understanding of the environmental conditions to which the material will be subjected. After all other factors have been considered, the final choice of a material must be based on its availability in the desired form, service temperature and stress, expected service life, and permissible deformation or strain during this expected life.

For purposes of this discussion, the use of creep and creep-rupture data has been arbitrarily divided into three categories:

1. Creep in stationary equipment.
   Steam power, power gas turbines, etc. This type of equipment involves long-term creep to cover a period of 10 to 20 years of continued operation.

2. Creep in air-borne equipment.
   Aircraft gas turbines, rocket motors, missiles, etc. This type of equipment involves short-term creep with time periods from seconds for

Ward Simmons has participated in numerous studies relating to high-temperature properties of materials. Among other things, he has helped to guide an investigation of the effect of manufacturing variables on the high-temperature properties of steels and shared responsibility for directing a national program for evaluating super-alloys for use in aircraft jet engines. Since joining Battelle, Simmons has also aided in the development of equipment and techniques for vacuum-creep studies, and he has directed investigations of the high-temperature properties of cermets; of newer metals such as titanium, zirconium, beryllium, etc., and their alloys; and of plastics and plastic-glass laminates. Earlier, he was a metallurgist with the American Steel and Wire Company at Duluth. He is author of more than a dozen publications, including several extensive series of reports on high-temperature steels prepared for the American Society for Testing Materials.

rockets to several thousand hours for commercial aircraft engines.

3. Creep in airframe structures.
   This application involves small amounts of creep, usually less than 0.5 per cent plastic deformation, and relatively short times, at present, of certainly not more than a few hundred hours.

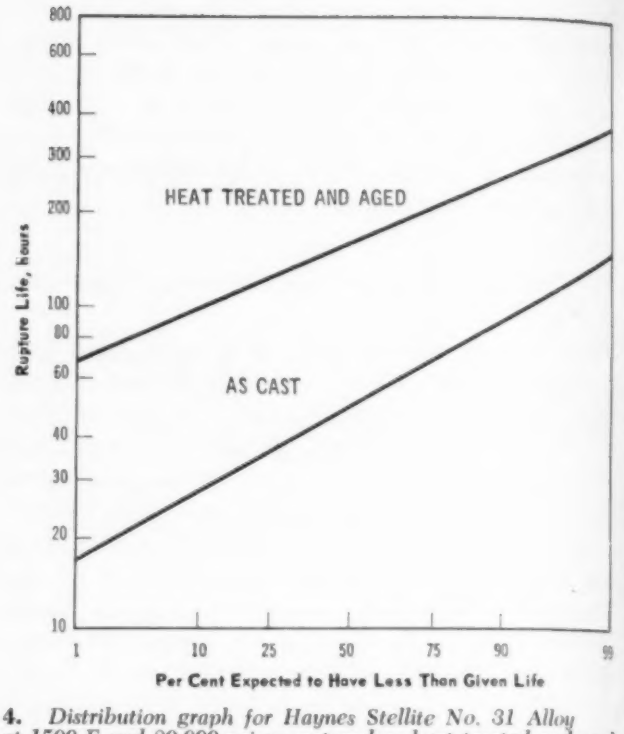
The need for consideration of creep data in airframe design is of comparatively recent origin, and is limited to structures in which aerodynamic heating and heating caused by close proximities of jet engines can be expected. Since the problem of creep is new in airframe design, this aspect of creep-data application will be emphasized in this article.

This article is intended to indicate in a general way the means by which creep and creep-rupture data are used in the design of equipment intended for operation at elevated temperatures. No attempt can be made in this limited space to discuss all of the technical details involved or to treat those discussed exhaustively. Though these limitations may oversimplify the problems, they do allow illustration of the basic principles.

Creep in Stationary Equipment

Probably the first application of creep data to design was in the steam power industry. By the early 1920's, a considerable back-log of experience had been built up in the design of steam generation equipment, and design stresses were based on the reports of the Boiler Code Committee of the American Society of Mechanical Engineers. As creep and rupture data became available, they were taken into consideration, along with past experience, by the Boiler Code Committee in determining maximum allowable working stresses.

Materials applicable to the design of equipment such as boilers, steam turbines, steam piping, oil refinery equipment, and power gas turbines must receive careful consideration. Since such equipment is intended to have a service life of 10 to 20 years or more, the laboratory test data must be determined in long-time tests, although judicious extrapolation of data from shorter tests is permissible. Creep and rupture (or stress-rupture) tests of 2000 to 10,000 hours' duration are commonplace, and some tests are run to longer times. One creep test of a low-alloy steel was carried out to over 10 years' duration by the General Electric Company. The longest creep test ever made at Battelle Memorial Institute was carried out on a 0.35 per cent carbon steel at 850 F and 7500 psi. This test had



4. *Distribution graph for Haynes Stellite No. 31 Alloy at 1500 F and 30,000 psi as cast and as heat treated and aged.*

an average second-stage creep rate of 0.00007 per cent per hour and was discontinued after almost 25,000 hours, still in second-stage creep.

Creep and rupture tests are normally made at constant temperature and load with various stresses being used to yield a family of curves as shown in Figure 2. The second-stage or minimum creep rates from these curves and the rupture times from the higher load tests are usually plotted against stress as shown in Figure 3. Log-log graph paper is normally used because the data often plot as straight lines on this type of paper, making a reasonable extrapolation of the data a simple matter.

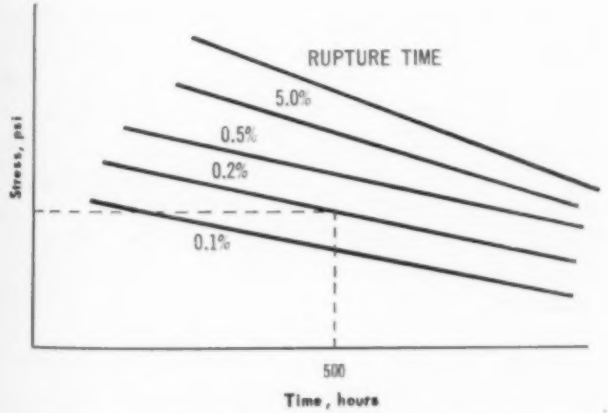
In setting allowable stresses for the design of long-time equipment, the stress to produce a creep rate of 0.00001 per cent per hour (1 per cent in 100,000 hours) is often used as the basis, with a suitable safety factor. Sometimes the stress to produce rupture in 100,000 hours is used. Generally speaking, extrapolation to 100,000 hours indicates that the stress for this rupture time is frequently, though not always, about double the stress required to produce a creep rate of 0.00001 per cent per hour (1 per cent in 100,000 hours). No matter what basis is used in arriving at the allowable stresses for long-time design, a reasonable safety factor can be used. This is a fortunate situation but it does not apply to the design of aircraft components where every extra pound is multiplied many-

fold in decreased pay-load carrying capacity of the aircraft.

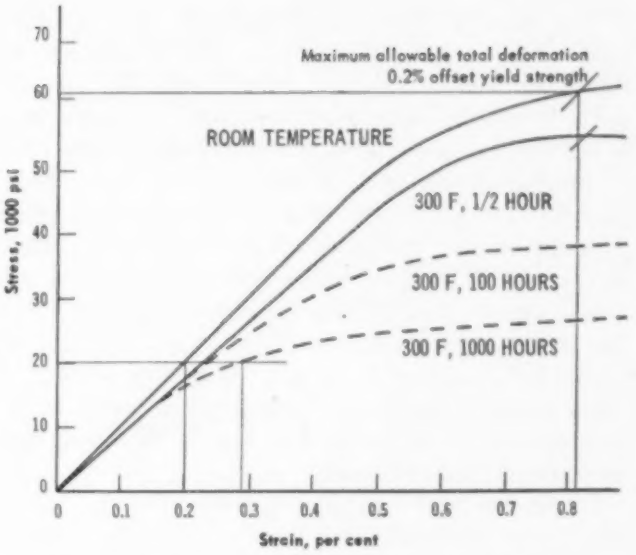
Creep in Air-Borne Equipment

With the development of the aircraft engine turbo-supercharger and the gas turbine jet aircraft engine, the use of metals at high temperatures and stressed for short times, usually less than 1000 hours, became a critical problem for the designers and the metallurgists. In contrast to long-time design, where the emphasis was on creep rates for determining allowable stresses, jet engine materials were evaluated and selected on the basis of rupture strength (the stress to produce rupture in a given time, such as 100 or 1000 hours).

The designer of aircraft components is highly weight conscious. Parts must be as light and strong as possible, but they must not fail in service. This would not be too difficult to accomplish, without over-design, if the parts made from one alloy all had the same strength. Unfortunately, variations in the strength properties of an alloy can be quite large, as shown by the scatter of rupture test results. In effect, the range of properties forces the designer to base his design on the minimum properties determined in the laboratory. Figure 4 indicates the scatter that can be expected in a cast cobalt-base alloy (approximately 27 Cr, 10 Ni, 7.5 W, balance Co) in both the "as cast" and heat-treated conditions. As an example, suppose 100 specimens of the "as cast" alloy were tested at 1500 F and 30,000 psi: one specimen would be expected to rupture in 17 hours, 50 specimens in 50 hours, and all but one specimen would have failed by 150 hours. Heat treating the alloy by heating at 2225 F and aging at 1300 F for 16 hours increased the strength considerably and decreased the scatter slightly, as indicated by the decreased slope of the curve. This type of data makes it easy to understand why, even with all of the engineering know-how that has accumulated during the last decade, it is still the engine tests that give the final answer as to the adequacy of materials and design.



5. *Design curves relating the time and stress for various amounts of strain and rupture at constant temperature.*



6. *Stress-strain curves at room temperature and 300 F and schematic isochronous stress-strain at 300 F for an aluminum alloy.*

Most components no longer fulfill their original function after they have deformed by an amount fixed by the design. Thus, since the amount of deformation at rupture is variable, creep-rupture data must always be used with a safety factor. In view of this, in recent years a more precise criterion than rupture strength has frequently been used in design and for evaluating materials. It is the stress to produce a given amount of strain in a given time, as for example, 0.2 per cent deformation in 500 hours. Data for this type of evaluation are obtained from creep-rupture and creep curves similar to those in Figure 2 and are plotted as shown in Figure 5. From this plot, the stress to produce 0.2 per cent strain in 500 hours can easily be determined.

Creep in Airframe Structures

Conventional aircraft are designed to operate at atmospheric temperatures and their design is based on conventional short-time stress-strain data obtained at room temperature. As long as aircraft operate at normal temperatures, creep is not a problem, but aircraft are now being designed to fly at supersonic speeds at which aerodynamic heating will cause the airframe temperature to increase to such an extent that creep must be considered.

The creep problem in a complicated structure such as a wing is quite different from the creep problems discussed earlier in this article. Normally, stressed parts at high temperatures are free to deform very much like a test specimen in the laboratory. However, a structure composed of tension and compression members cannot deform freely as can a turbine blade in a jet engine. Inasmuch as it is restrained, some members will be upset and others elongated, but the over-all dimensions may not change greatly until failure occurs suddenly with little or no warning. Failure might be visualized as similar to the toppling of a radio antenna tower in a high wind. As soon as the compression members begin to buckle, the tower loses its strength and collapses.

It appears that airframes intended to operate at elevated temperatures will be designed very much as conventional airframes are, and the design will then be evaluated for creep. This approach seems necessary because creep data cannot be applied to the design formulas which must be used. The situation is similar to that of fatigue (the decrease in strength of metals under cyclic loading and vibration) in conventional airframe design. Airframes are difficult to design for fatigue, but the design can be evaluated for fatigue and modified if necessary.

To simplify the task of evaluating the airframe design for creep it is desirable to supply the designer the creep data in the form of curves similar to those with which he is familiar. Figure 6 shows typical stress-strain curves for an aluminum alloy at room temperature and at 300 F, and isochronous (constant-time) stress-strain curves for 100 and 1000 hours at 300 F. Since stress-strain curves are basic to the airframe designer, creep data in the form of isochronous stress-strain curves are very useful. The isochronous curves are constructed from creep curves similar to those shown in Figure 2 by plotting the strain produced by different stresses at constant times. The isochronous curves in Figure 6 are schematic and should not be regarded as actual test data.

Within the straight-line portion of the stress-strain curves, the stress is proportional to the strain, and the behavior indicated is elastic. At stresses above the straight-line portion of the curve, the amount of deviation from a straight line represents plastic strain or permanent deformation. The 0.2 per cent offset yield strength is the stress which produces 0.2 per cent permanent deformation. The relationship of the isochronous curves to the stress-strain curves is such that the points at which the isochronous curves deviate from the stress-strain curves indicate the stress at which creep becomes an important factor under the conditions of time and temperature for which the curves were prepared. Thus, this information can be presented to the designer as a series of curves similar to those with which he is completely familiar.

An approximation of the amount of allowable deformation available to the designer of a bomber, for example, is given by Figure 6. If the maximum allowable total deformation is given by the strain at the 0.2 per cent offset yield strength, this limit is about 0.8 per cent. If the design of a conventional bomber is based on one-third of the room-temperature yield strength for level flight conditions (exclusive of maneuver and gust loads), steady-state flight stresses with this particular aluminum alloy is 20,000 psi and represent 0.2 per cent strain. This is well within the region of elastic behavior and creep does not enter the picture.

However, suppose that the bomber is expected to be heated aerodynamically to 300 F. The design stress of 20,000 psi is then above the point in Figure 6 where the isochronous curves leave the straight-line portion of the 300 F stress-strain curve, and creep will occur. Under the minimum conditions of level flight, the 300 F—1000 hours curve indicates that approximately 0.3 per cent strain will occur, leaving 0.5 per cent strain remaining to reach the 0.8 per cent limit. Now, realizing that maximum maneuver and gust loads may reach 40,000 psi and remembering the rapid rate of creep which occurs during the first stage of creep, it is obvious that the bomber could not fly under these conditions for more than a few missions without exceeding the remaining 0.5 per cent total deformation and running the risk of immediate failure.

Under the above conditions, the material under consideration was satisfactory for a conventional bomber, but was not suitable for the 300 F bomber, and another material of superior creep resistance would be needed.

Research in the field of creep and related elevated temperature properties of metals has increased tremendously in recent years. This has resulted in the amassing of data for design purposes. However, in addition, many fundamental creep studies are in progress aimed at an understanding of the basic principles of creep. Once these principles are understood, it may be possible to reduce the time and effort required to develop and test new alloys for elevated temperature applications.

NOTES from BATTELLE

ENAMEL ADHERENCE STUDY

Evidence that good adherence of enamels to metals is largely a chemical phenomenon has been reported by ceramists at Battelle. Studying what makes porcelain enamel stick to metal, they have uncovered basic information that gives a more accurate understanding of the enamel-to-metal bond than has been available previously. To technologists, this development indicates a process by which many more metals may be coated with porcelain enamels and provides an insight into means for improving compositions and processing methods.

B. W. King, H. P. Tripp, and W. H. Duckworth reported the results of their investigation at the 58th Annual Meeting of the American Ceramic Society in New York. They pointed out that previous ideas about enamel-metal bonding accounted for many of the facts known about bonding and determined the direction of many of the studies on the subject. The new theory, however, based on experiments conducted at Battelle, provides a much fuller explanation of why porcelain enamels stick to metals and suggests a new line of research attack.

This is what ceramists at Battelle believe causes bonding: Right at the surface of the metal, where the metal and the enamel come in contact, a layer of metal atoms combines with oxygen atoms in the enamel, and becomes, in effect, a part of both the metal and enamel structure. The metal atoms retain a strong attraction toward other metal atoms farther down in the metal. Likewise, the oxygen atoms are attracted to other atoms farther up in the enamel.

Most current knowledge about enamel-metal bonds has resulted from noting what materials and processing methods create good bonds. Because better bonds had often been achieved when the metal surface was roughened before enameling, it was generally believed that a rough surface was necessary for good bonding between the metal and the enamel. Institute ceramists demonstrated the relative unimportance of a rough metal surface with an experiment in which highly polished iron was coated with well bonded enamel just by insuring that the proper chemicals were present in the enamel to form the metal-oxygen layer of atoms between the metal and the enamel.

This fundamental research, conducted at Battelle, indicates the specific conditions required to produce excellent bonds between metal and enamel. The research was jointly underwritten at Battelle by a group of companies in the porcelain industry.

IMPROVED SOFT SOLDERS

The use of automobile radiators with operating pressures up to 16 psi calls for solders stronger than those currently in use. Moreover, the solders must retain their properties at the higher temperatures that result.

Battelle technologists have been investigating the problem of developing improved solders for the Tin Research Institute, in anticipation of the demands that may result from greater operating pressures in radiators. They evaluated a number of altered tin-lead solders under cyclic loads at 225 F. Generally, solders with high tin content showed longer life under such loading.

H. E. Pattee and R. M. Evans of Battelle report that additions of germanium, nickel, or cerium (used only in concentrations of 0.2 weight per cent) improved the ability of tin-lead solders to withstand elevated-temperature usage. Gains from these additions appear more pronounced if the tin content of the solder is high. Low concentrations of zinc, bismuth, and antimony are also beneficial, though high concentrations have detrimental effects.

XEROGRAPHIC DEVELOPMENTS

In the years since the idea for xerography was first brought to Battelle for development, that photographic process has found numerous important uses. Based entirely on physical and electrical phenomena, xerography is a completely dry photographic process depending upon:

1. Formation of an electrostatic image on a photoconductive insulator by exposure to light;
2. Development of this image by a finely divided powder;
3. Transfer of this powder image to a permanent support such as a sheet of paper;

4. Fixing the powder image as by moderate heating.

Several studies relating to additional xerographic developments are being currently sponsored at Battelle. The investigations include : (1) preparation of lithographic plates by xerography for printing photomaps, for the U. S. Army Engineers Corps; (2) reversal development, in which positive xerographs are prepared from negative photographic transparencies, for the U. S. Signal Corps; and (3) recording by xerography, permanent black and white radar images directly from an electron beam, for the U. S. Air Force. The latter work is directed to the development of design data for "bread-board" apparatus.

* NEW LUBRICANT

Studies of new types of synthetic chemicals, called chlorofluorocarbons, show that they have exceptional potentialities as lubricants. Technologists at Battelle found that when used as lubricants, these chemicals exhibit great thermal stability, good load-carrying capacity, and stability in oxygen. Their extreme high-temperature stability is apparently related to the very strong intramolecular bonds, resulting from the presence of the fluorine atoms, while the complete absence of hydrogen in the chlorofluorocarbon molecule contributes to its stability in the presence of oxygen. The chlorine atoms are thought to be responsible for the high load-carrying capacity exhibited by these compounds.

The chlorofluorocarbons are useful as lubricants for bearings operating under high loads, as lubricants and sealants for bearings and pistons operating under severe oxidizing conditions, such as in oxygen compressors and pumps, and as additives to increase the load-carrying capacity and lubricity of natural and synthetic lubricants without diminishing the stability of the latter. Reasonable compatibility of these chlorine- and fluorine-saturated carbon-chain compounds with other lubricants makes these latter uses technically feasible.

This research at Battelle was sponsored by the M. W. Kellogg Company, Jersey City, New Jersey, which manufactures chlorofluorocarbons by a process known as telomerization.

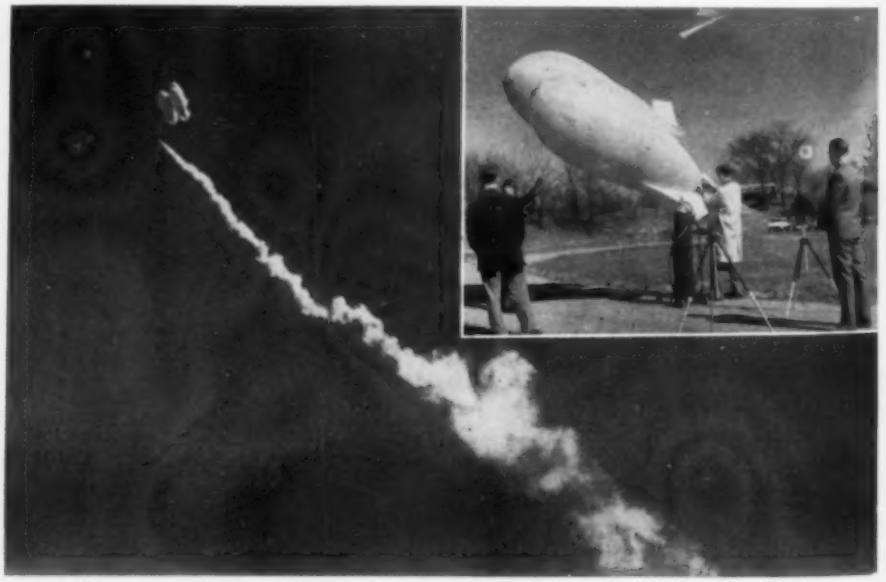
* HYDROGEN IN STEEL

Hydrogen may cause several types of defects in steel, and its presence in the metal is never beneficial. Indeed, hydrogen is unique among alloying elements in that it reduces the ductility of steel without increasing its strength. Fortunately, the amounts of hydrogen retained in many grades, from steel-making operations, do not cause commercially important defects. However, it may cause significant defects in killed steels for fabrication into heavy sections. In general, the occurrence of hydrogen-caused defects is greater in alloy than in carbon steels.

E. R. Slaughter, Battelle metallurgist, reported the following four principal defects in steel by hydrogen to the Operating Metallurgy Session of the recent National Open Hearth Conference.

Porosity. Hydrogen, which is more soluble in liquid steel, tends to be rejected by the metal as it solidifies.

(Continued Opposite Inside Back Cover)



The kytoons shown being prepared for use (inset) and high in the air are used by Battelle technologists in air-pollution studies. The smoke streaming from the kytoons is from smoke bombs which are triggered electrically. The dispersion of the smoke is then recorded photographically for study. The photos show how stack gases disperse at various levels, and the data is used, for example, to help determine the best height for chimneys to be built at a new power-plant site.

CONTINUED FROM PAGE 16

As a result, a part of the hydrogen present may be liberated as gas, to cause blow-hole type porosity or aggravate center-line shrinkage. Hydrogen can cause porosity in steel castings regardless of composition, but it is particularly troublesome in high-chromium grade ingots.

Flaking. Flakes are ruptures in massive steel billets, forgings, or rolled products which are caused by hydrogen in the presence of thermal or transformation stresses. Stresses must exist in the steel for a period ranging from several hours to more than a day while the metal is below 400 F in order to cause flaking. Steels with greatest hardenability are most susceptible to flaking.

Loss of Ductility. This defect, also known as hydrogen embrittlement, may affect all ferritic steels and, to a lesser extent, austenitic steels. Hydrogen, in this, as in the case of flaking, is introduced during the steel-making operation or during pickling and electroplating.

Delayed Brittle Fracture. These fractures are encountered in steel parts heat treated to more than 180,000 psi ultimate tensile strength. They occur when parts are subjected to static loads far below the yield point and after delays of several months. It is generally agreed that hydrogen is necessary for the failures to occur, and that it is introduced from plating or pickling operations.

* COKE STRENGTH

A knowledge of the mechanical strength of coke at elevated temperatures is important to those using the fuel in iron and steel processing. Battelle technologists were asked by the United States Steel Corporation to investigate methods for determining the elevated-temperature strength of metallurgical coke. The results of the study were reported to the 60th Annual Meeting of the American Foundrymen's Society by John Varga, Jr., and H. W. Lownie, Jr., of the Institute.

The Battelle technologists, as the basis for determining mechanical strength, developed a new type of apparatus consisting of a silicon carbide tube for containing the coke, surrounded by an insulated combustion chamber. The entire assembly can be rotated end over end by a variable-speed drive while heating is in progress. The equipment is capable of tumbling coke at temperatures up to 2500 F. The mechanical strength of the coke is measured in terms of the proportion of coke particles retained on selected sizes of screens before and after tumbling at the various temperatures.

Experiments were conducted at room temperature, 1500 F, 2000 F, and 2500 F with a considerable number of cokes. The evaluations showed that the mechanical strength of the coke continued to be affected by increasing temperatures to 2500 F. The experiments also showed that cokes having similar room-temperature strengths often exhibited widely differing elevated-temperature strengths. In the case of several cokes evaluated, the proportion of particles retained on a one-inch screen decreased by about 50 per cent after heating.

* Preparations are under way for the investigations which are to be carried out in Battelle's nuclear reactor for the Esso Research and Engineering Company. The investigations themselves will begin as soon as the research reactor reaches full power.

Esso Research has contracted with Battelle for a comprehensive study to develop widespread atomic energy applications in the oil industry. Institute scientists will conduct the actual experiments which are specifically aimed at perfecting ways of using nuclear radiation in petroleum refining and in the production of petrochemicals. Esso anticipates that the reactor program will confirm and extend the scope of possibilities for the use of irradiation processing in the petroleum industry as already indicated by its own previous investigations.

* Albert C. Beer has been appointed an assistant technical director at Battelle. In his new assignment, he will give increased attention to guiding applied research in the solid state and semiconductor fields at Battelle and to the encouragement of fundamental research in his fields of interest.

Since joining the Institute, his accomplishments have included theoretical interpretative studies, investigations of the galvano-magnetic properties of germanium and indium antimonide, participation in the development of aluminum antimonide, and analyses of high-carrier-density semiconductors. Previously, at the Applied Physics Laboratory of John Hopkins University, he had investigated problems relating to the development of guidance systems for missiles and aircraft.